

High Power Tests of Millimeter Wave Accelerators

Mohamed Othman

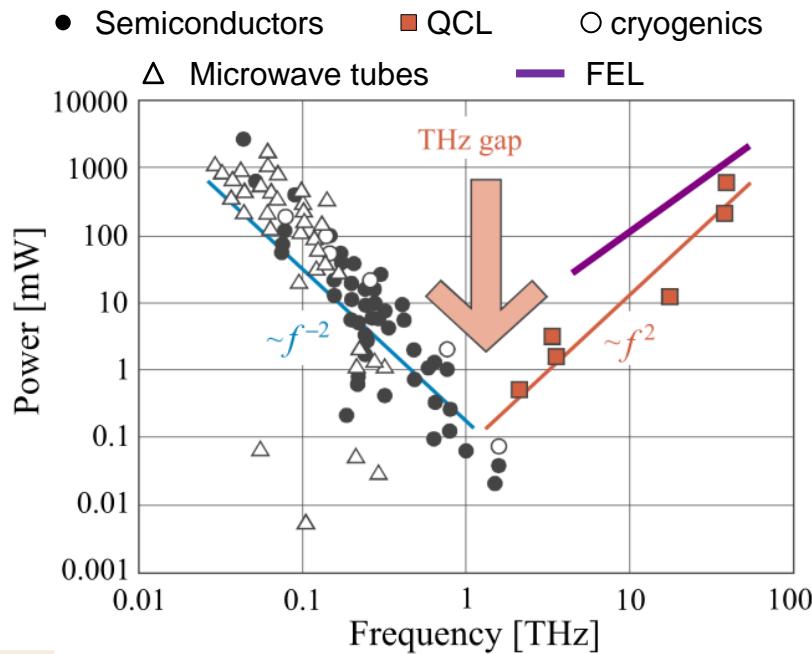
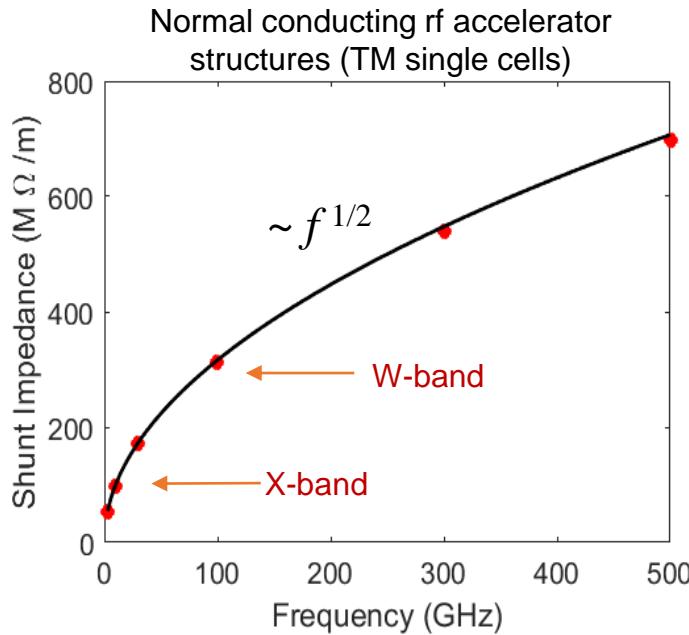
SLAC National Accelerator Laboratory

April 20, 2021

The 13th Workshop on
Breakdown Science and
High Gradient Accelerator
Technology

Terahertz-Driven Acceleration, Sources and Pulse Generation

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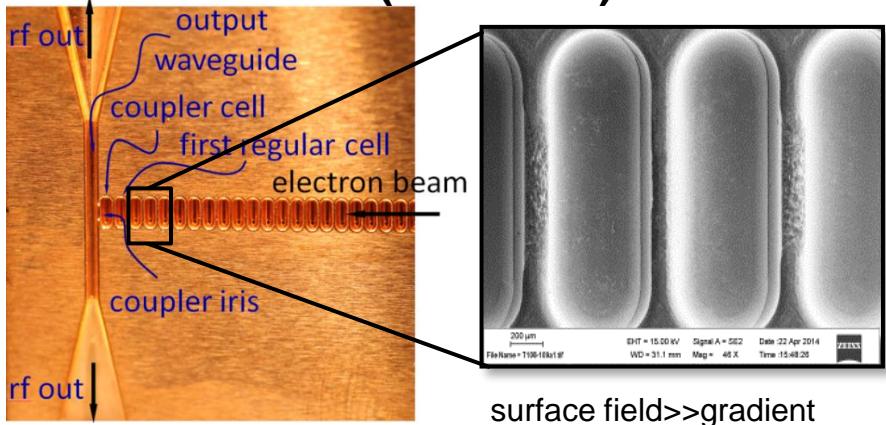
Need advanced techniques for high peak power narrowband THz sources
=> Efficient accelerators

Nature Photonics. 1 (2), (2007)
Science 318 (2007)
J Phys. D: Appl. Phys. 50.4 (2017)

THz Metallic Structures Holds the Potential for High-Gradient Accelerators: Beam-Driven Mm-Wave Structures

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- Beam driven (Collinear) acceleration



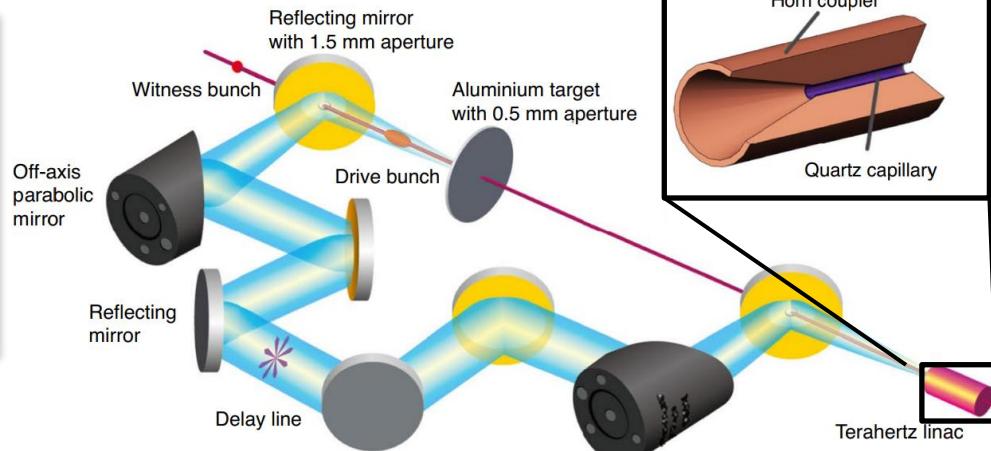
Accelerating gradient ~ 50 MV/m

Surface fields ~ 500 MV/m

Pulse length ~ 100 ps

Drive bunch 4 GeV, nC

Dal Forno et al., *Phys. Rev. Accl. Beams*, 19.1 (2018).



Accelerating gradient ~ 85 MV/m

Pulse length ~ 2 ps

Drive bunch 30 MeV, pC

Hanxun Xu, et al., *Nature Photonics* (2021).

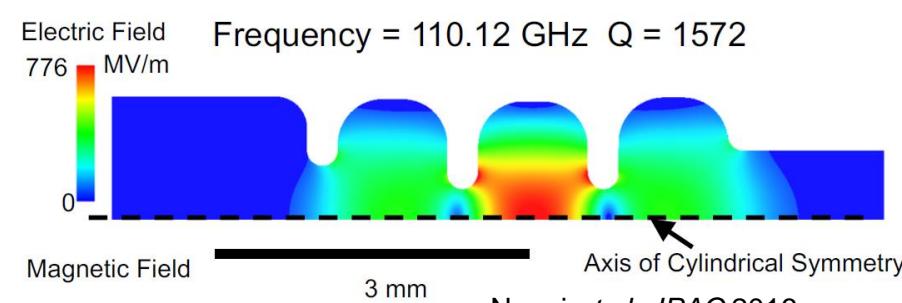
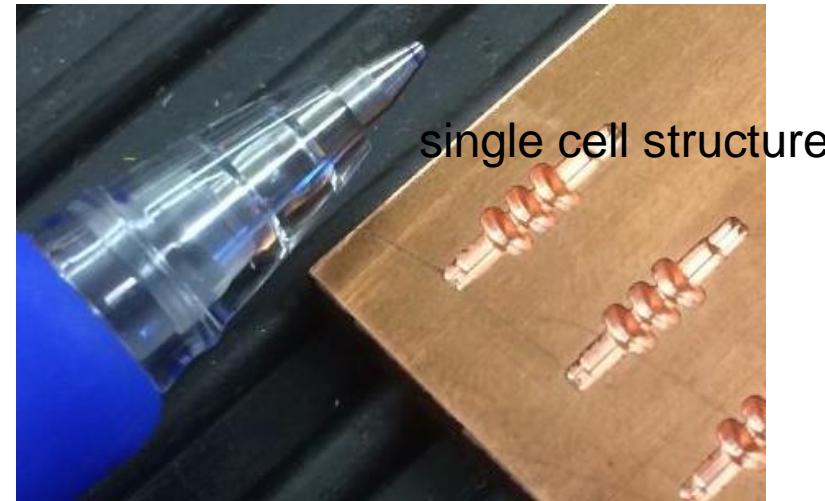
Characterization of externally-driven high gradient THz structures needed for achieving optimal operation

Prototyping and Assembly of Externally-Driven THz Accelerator Structures Using Split-Block Technology

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110 GHz single cell accelerator cavity

Iris thickness [mm]	0.2
Quality factor Q_0	3200
Shunt impedance [$M\Omega/m$]	360
$E_{\text{surface}}/E_{\text{acc}}$	2.27
Gradient E_{acc} [MV/m]	404
Pulsed heating [$^{\circ}\text{C}$]	70
Fill time [ns]	5



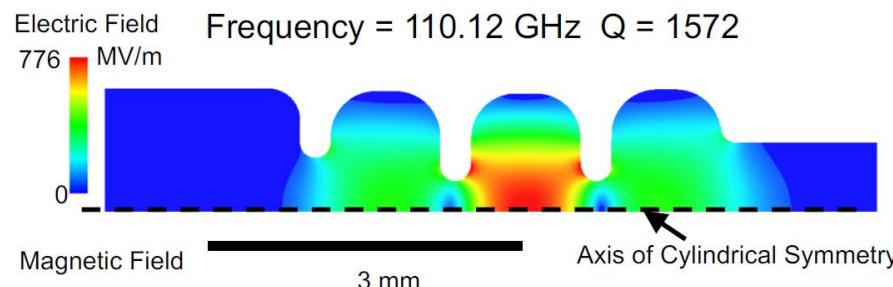
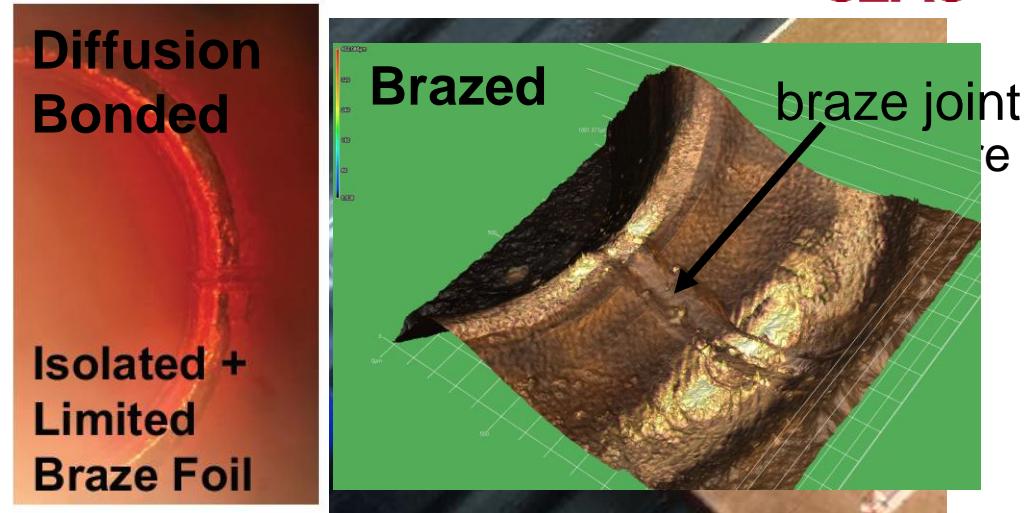
Future approaches include additive manufacturing

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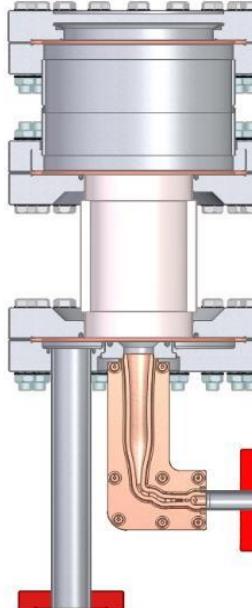
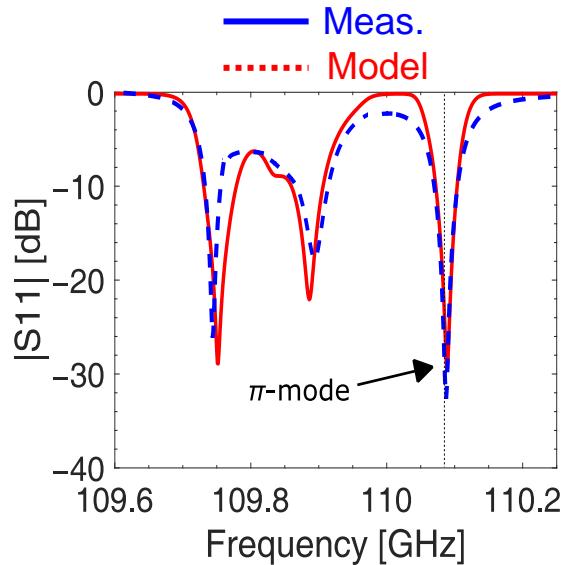
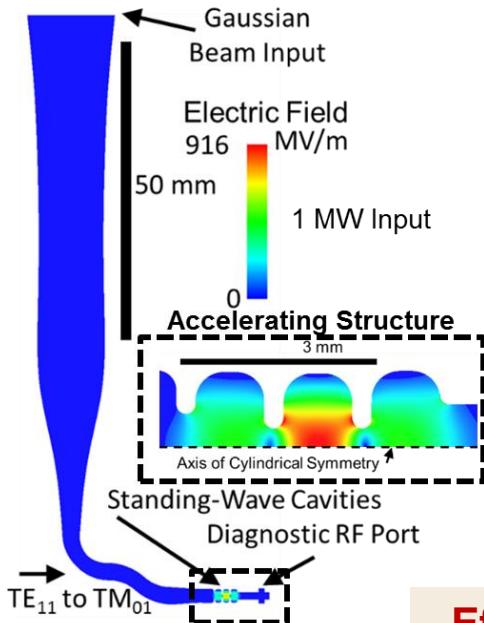


Future approaches include additive manufacturing

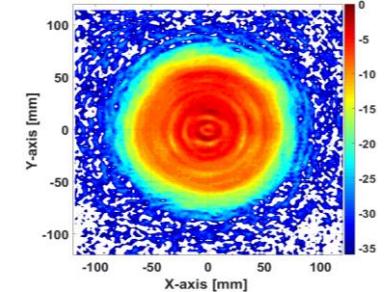
Efficient Excitation of THz Accelerating Structures Using Quasi-Optical Coupling of rf Power

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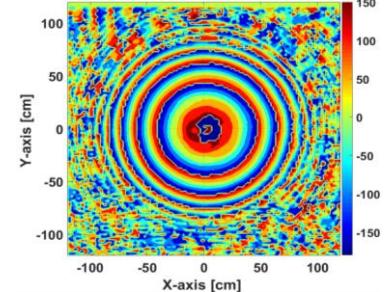
Free-space Gaussian beam coupled to structure
>90% efficiency



Measured Amplitude



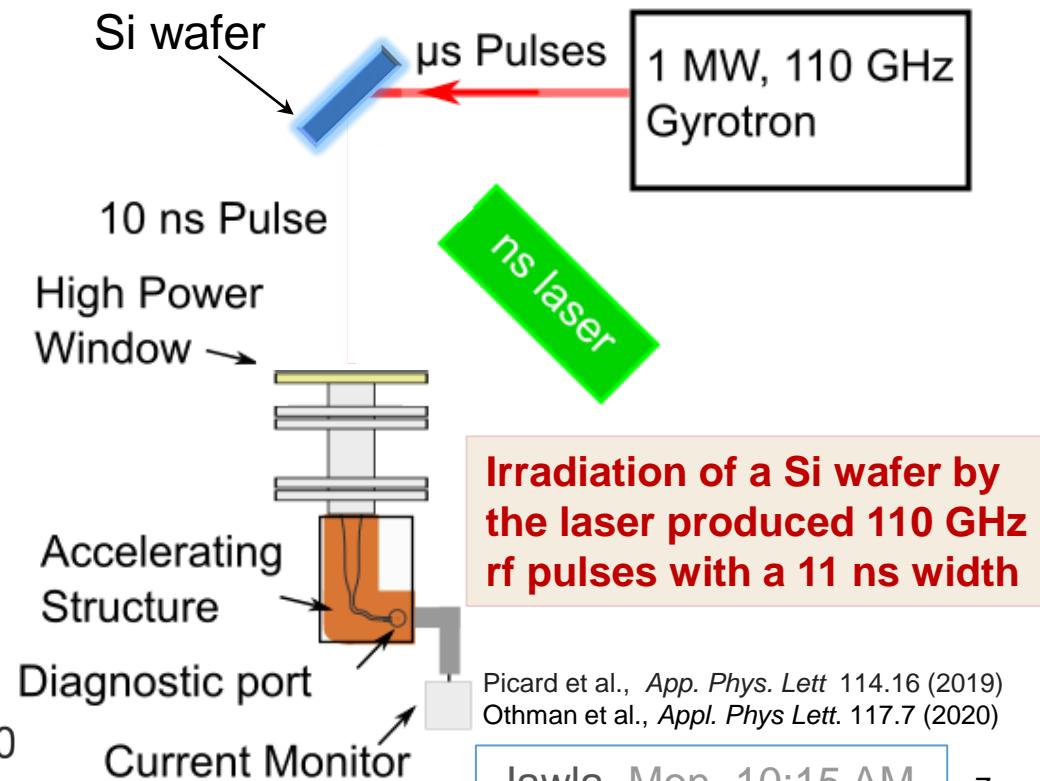
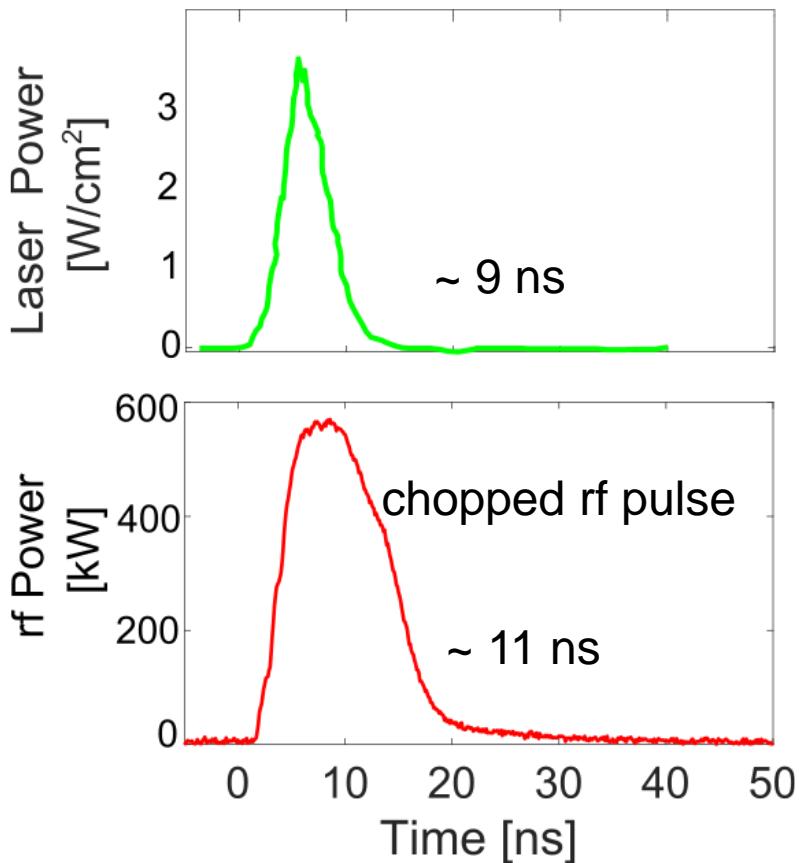
Measured Phase



Efficient coupling into narrow-band accelerating structures to avoid lossy waveguides

Laser-Based Semiconductor Switch for Nanosecond rf Pulse Shaping

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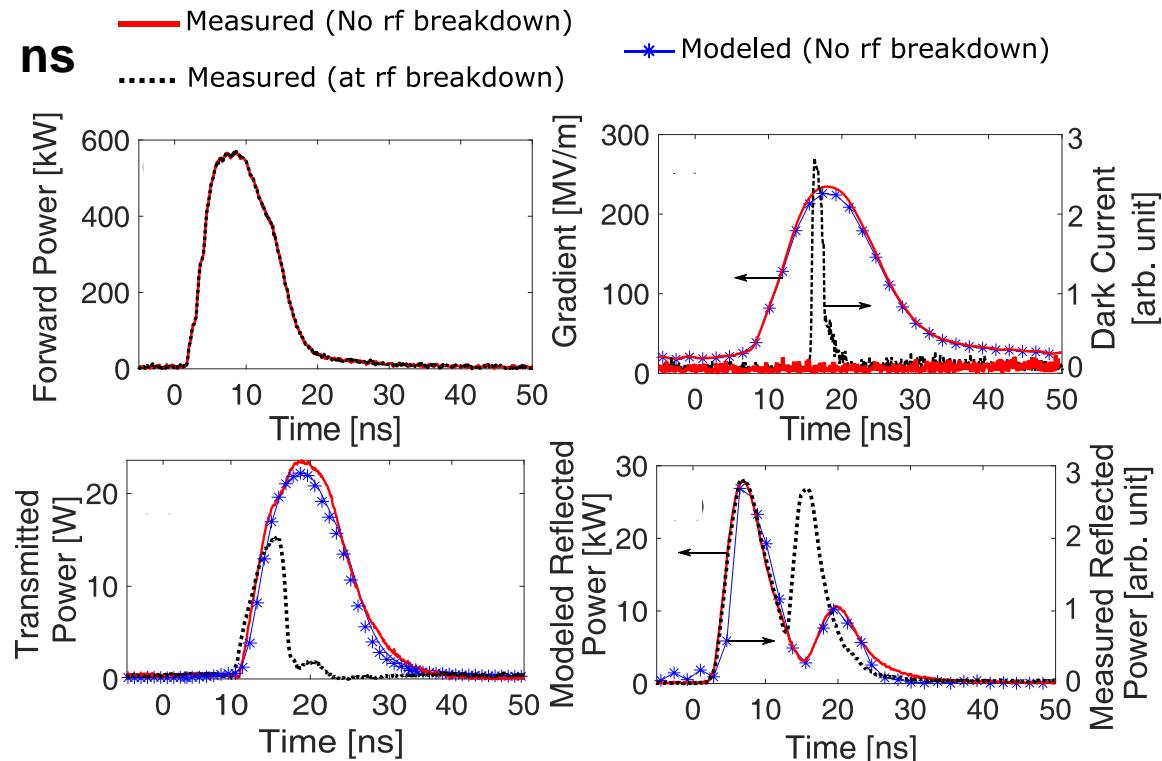


High Gradient Measurements at 110 GHz

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Highest Gradient at 570 kW @ 11 ns

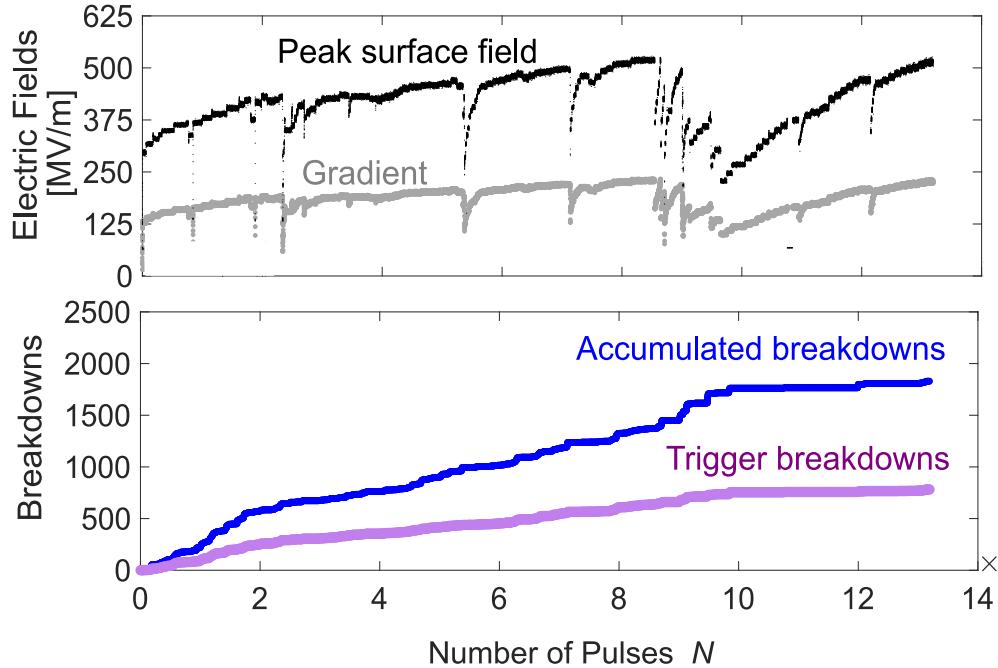
- Peak gradient 230 MV/m
- Peak surface field > 520MV/m
- Peak pulse surface heating < 40 °C indicating no damage



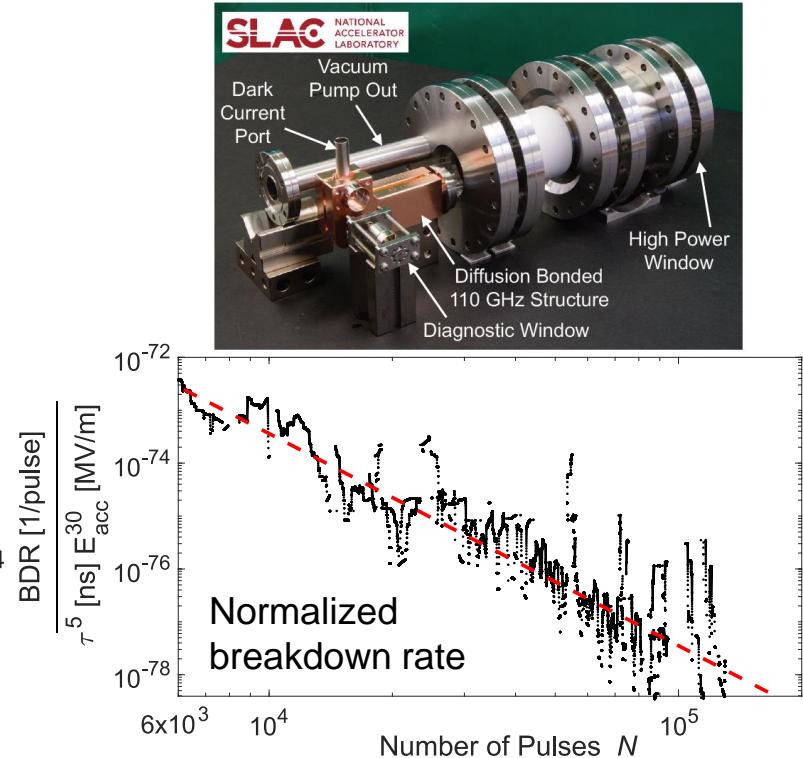
Reliable measurements of high gradient and rf pulses is crucial

Processing Timeline: Gradient of 230 MV/m at 10^5 Pulses

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Othman et al., Appl. Phys Lett. 117(7) 073502 (2020).



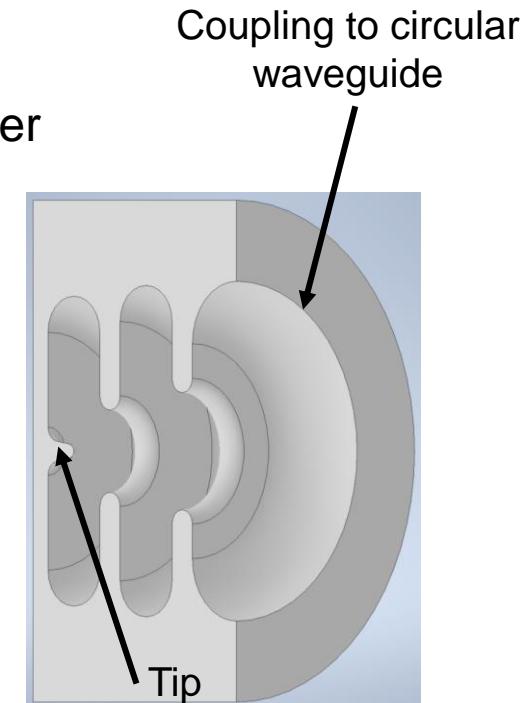
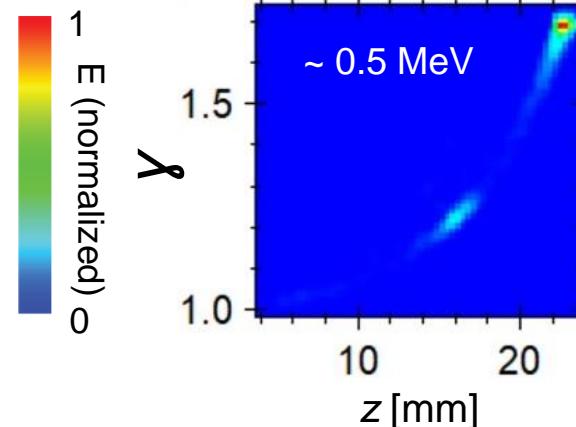
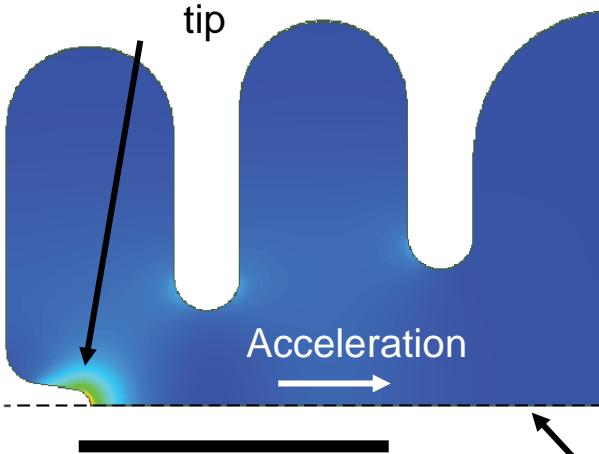
Rapid processing of the cavity is essential for high gradient applications

High Brightness Field Emission THz Gun

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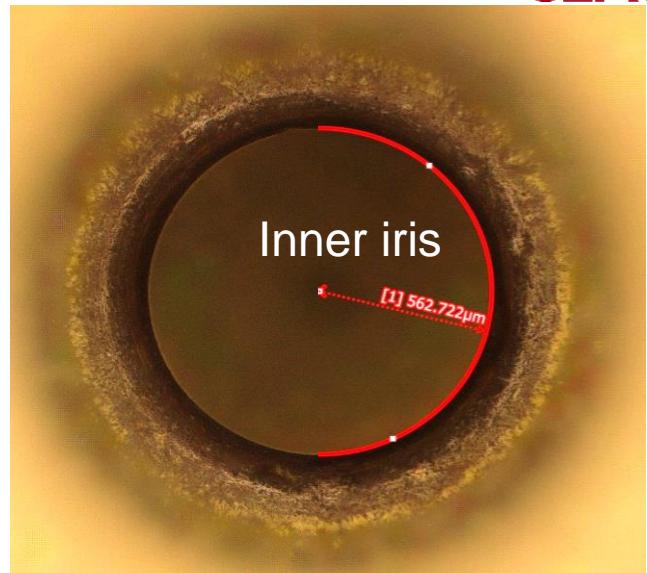
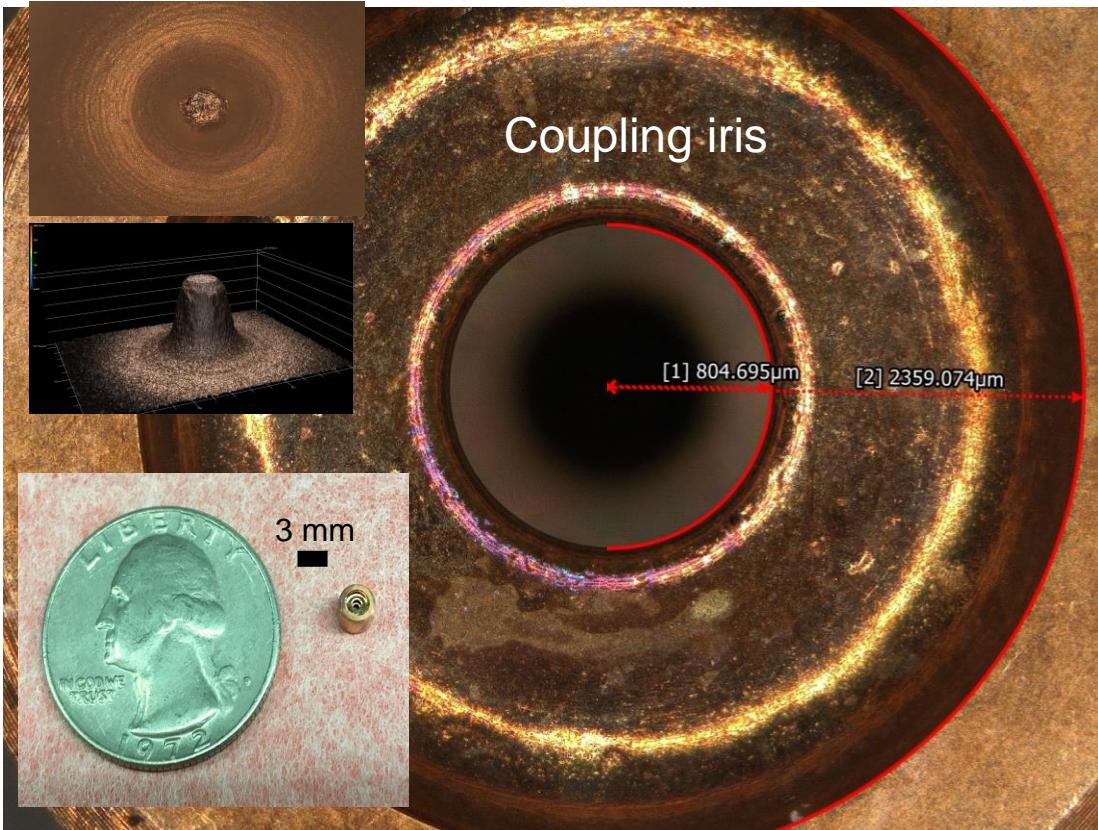
- Two cell gun with 50 μm radius copper tip
- On-axis coupling from 110 GHz gyrotron source
- Maximum field on the tip is 3.8 GV/m for 500 kW input power

Field enhancement at



Field Emission Gun Cells Fabrication and Assembly: Additive Manufacturing Tools

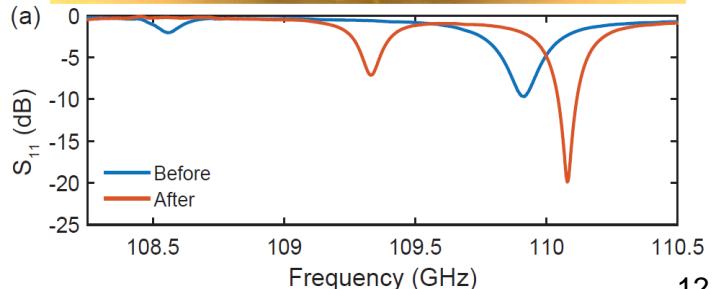
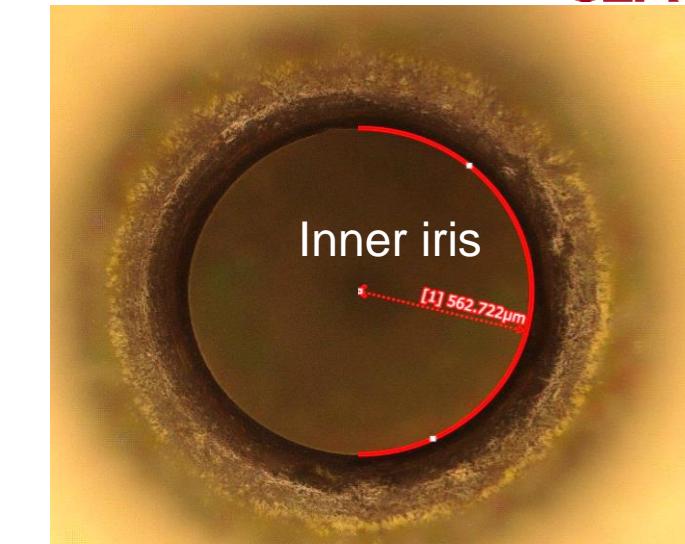
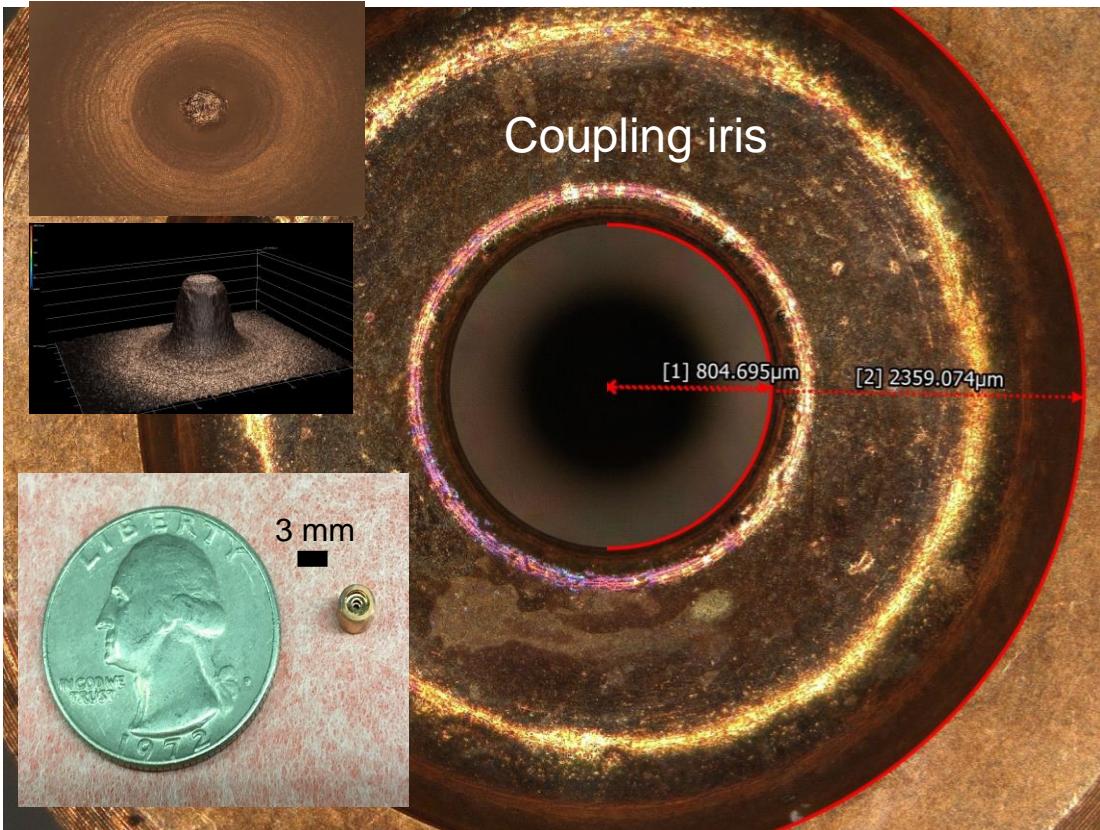
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Dimension	Design	Measured
Inner iris radius	0.268 mm	0.281 mm
Coupler radius	0.408 mm	0.402 mm
Waveguide radius	1.185 mm	1.180 mm

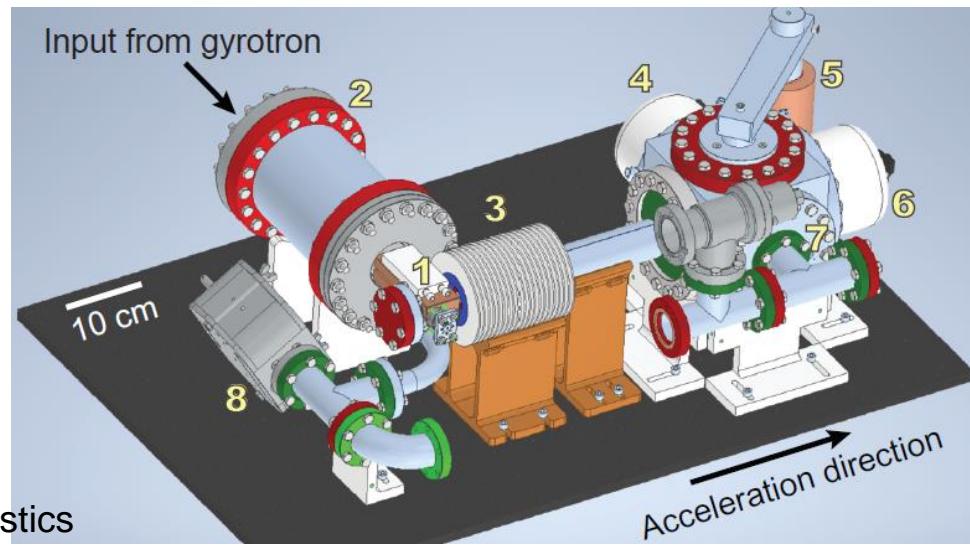
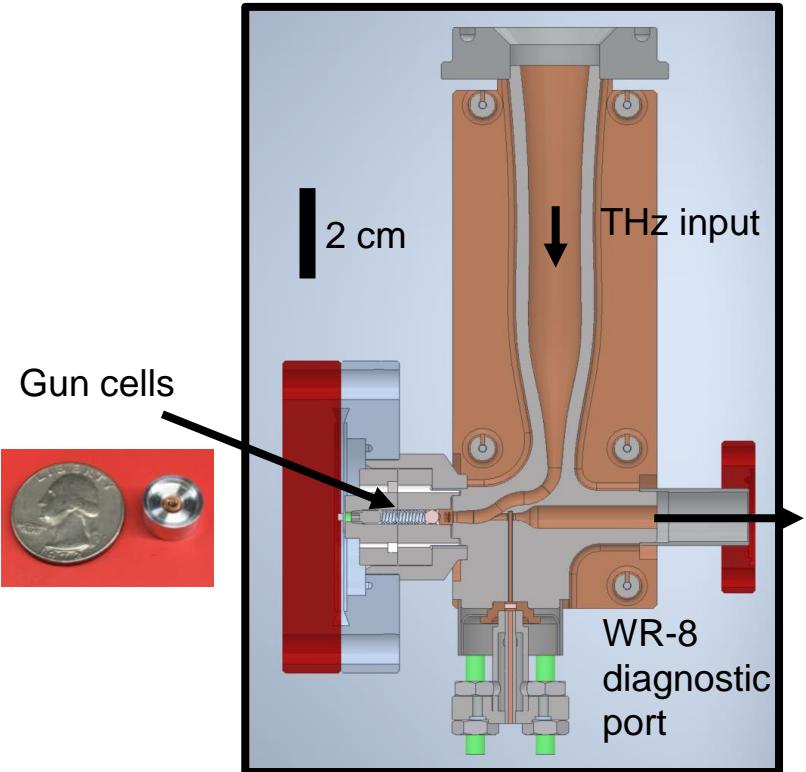
Field Emission Gun Cells Fabrication and Assembly: Additive Manufacturing Tools

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Field Emission Gun Cells Assembly and Beam Diagnostics

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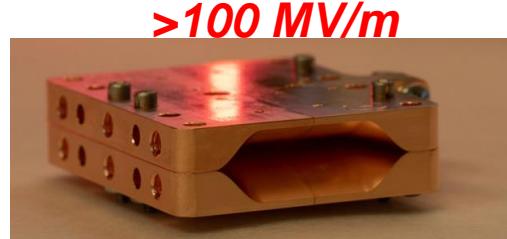


Demonstrate feasibility of using normal conducting, THz accelerating structures to create compact ultra bright electron sources for EM applications

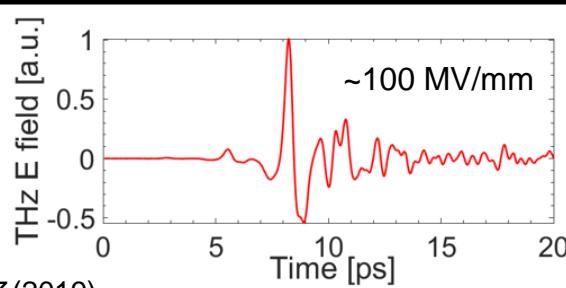
Novel Beam-Wave Interactions at THz Frequencies: Broadband THz Accelerator Structures [Picosecond pulses, ~ MW Peak Power]

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- Laser driven THz acceleration

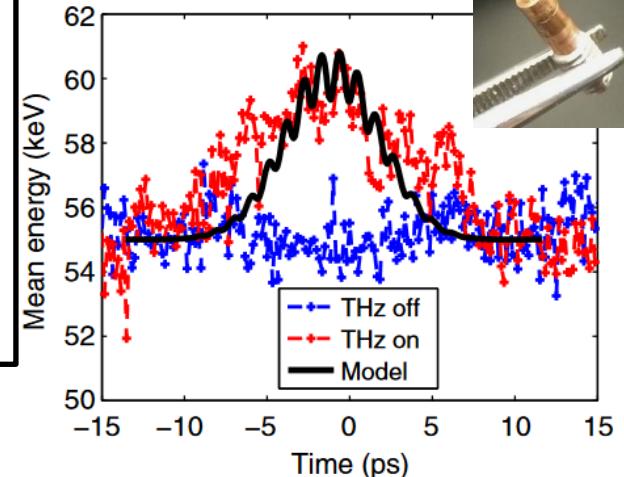


>100 MV/m

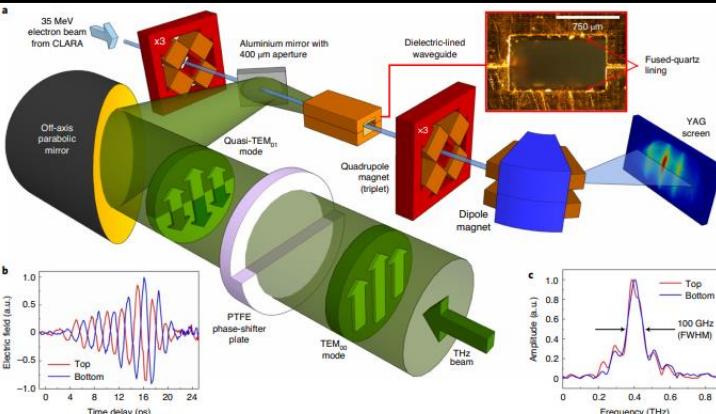


Othman et al., Opt. Express 27.17 (2019).
Snively, Othman et al., PRL 124.5 (2020).
Othman et al., arXiv preprint arXiv:2104.05691 (2021).

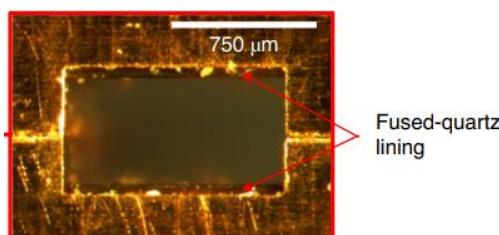
50 MV/m



Nanni et al., Nature Comm. 6 (2015).



2 MV/m

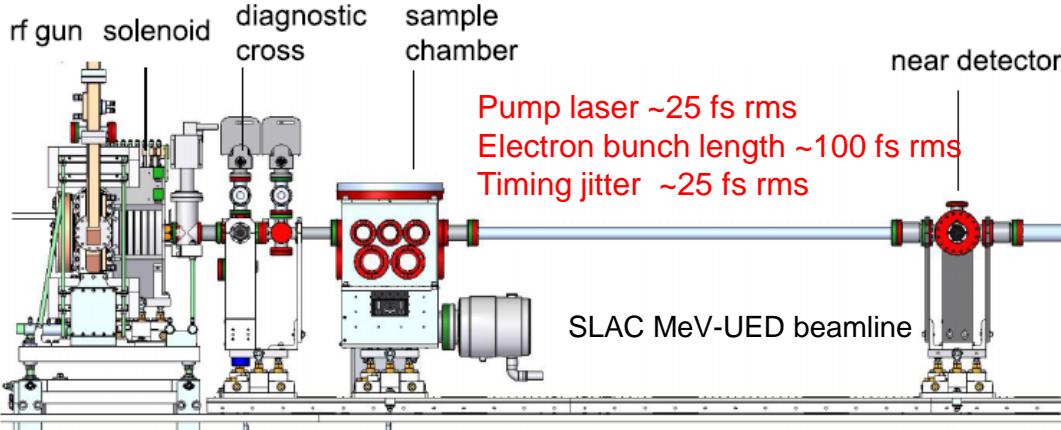


Hibberd et al., Nature Photonics 14.12 (2020).

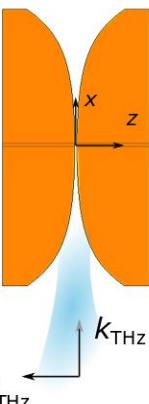
THz race heats up with new high gradient technologies

Ultrashort Bunch Generation for Ultrafast Electron Diffraction Using THz-Driven Compression and Time-Stamping

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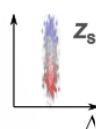


Weathersby, et al. *Review of Scientific Instruments* 86.7 (2015): 073702.

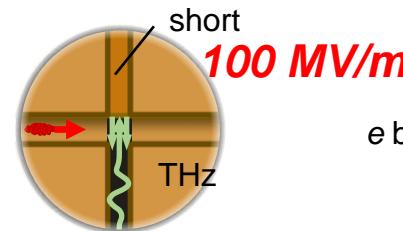


- Single cycle THz pulses
- High peak power for efficient
- Kick ~ 10 keV/100 fs

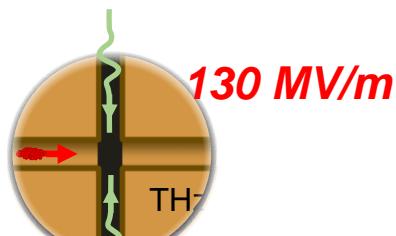
Othman et al., *Opt. Express* 27.17 (2019).



e beam



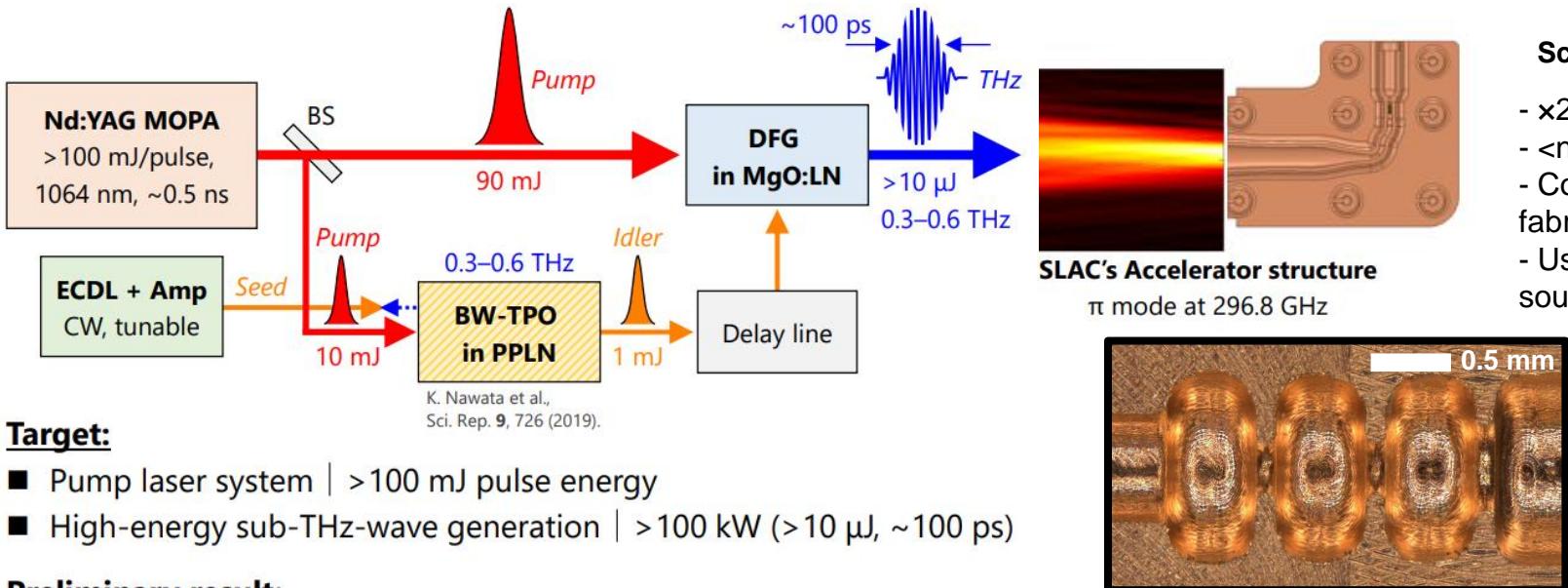
Snively, Othman et al., *PRL* 124.5 (2020).



Othman et al., arXiv preprint arXiv:2104.05691 (2021).

Narrowband High Gradient THz Accelerators: Leveraging laser-Driven THz Sources

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Target:

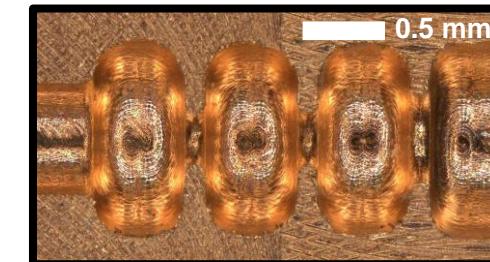
- Pump laser system | >100 mJ pulse energy
- High-energy sub-THz-wave generation | >100 kW (>10 μJ, ~100 ps)

Preliminary result:

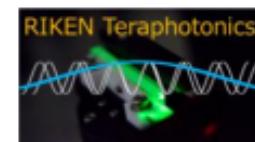
- 0.46-THz generation (unseeded BW-TPO & DFG) with 15-mJ pump laser system

Scaling to 300 GHz

- ×2 shunt impedance
- <ns fill time
- Compatible with fabrication
- Using laser-driven sources



Toward 100 MeV/m acceleration with laser-generated THz pulses



Summary and Outlook



- Mm-Wave/THz accelerating structures promise high gradient toward achieving GeV/m with compact footprint
- Performance of THz structures under high gradient depends on rf design, assembly and excitation
- High gradient structures at 110 GHz tested demonstrate record high gradient >230 MV/m and fast processing $< 10^5$ pulses
- Field emission gun is in line for testing (2021)
- G-band structure and THz accelerators are showing practical use

Acknowledgments

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INFN-LNF

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FermiLab

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RIKEN

Yuma Takida

Hiroaki Minamide

SLAC MeV-UED team